

DETERMINACIÓN DEL RIESGO DE INCENDIO EN UNA INSTALACIÓN DE SECADO DE ALPERUJO

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DETERMINATION OF THE RISK OF FIRE IN AN OLIVE-OIL MILL WASTE DRYER

ABSTRACT:

For the energy valorization of "alperujo", by-product of the olive oil two phases extraction process, it is necessary to perform a drying process to reduce moisture content from over 60% to less than 10% m/m w.b. In order to reduce primary energy consumption and get an economic return, usually in this kind of drying facilities Gas Turbine cogeneration (GT-CHP) is used as a heat source. In Spain, there have been recently some fires in this kind of GT-CHP facilities, which have caused big material losses. Therefore, the aim of this study is to determine experimentally and analytically under which operational conditions could occur self-ignition of alperujo in the drying process, and determine the actual fire hazard in this type of GT-CHP system.

For analytical study, was raised and validated mathematical model to calculate the temperature and composition of the flue gases into and out of the dryer, depending on the technical characteristics of the GT, atmospheric conditions, and the flow and moisture content of the treated biomass. The model also calculates the wet bulb temperature, which sets the maximum temperature reached by the biomass during the drying process and determine the amount of biomass that can be completely dry depending on the flow and the conditions of inlet combustion gas.

With these results and the minimum auto-ignition temperature of alperujo, experimentally determined according to EN 50281-2-1: 2000, it shows that there is no risk of ignition of alperujo under normal operating conditions in a rotary process of drying.

Keywords: Alperujo (olive-oil mill waste), drying of biomass, biomass auto-ignition, fire hazard, GT-CHP

RESUMEN:

Para la valorización energética del alperujo, residuo del proceso de extracción en dos fases del aceite de oliva, es necesario realizar un proceso de secado para reducir su contenido de humedad de más del 60% al 10% m/m en b.h. Con el fin de reducir el consumo de energía primaria y obtener una rentabilidad económica, normalmente en este tipo de instalaciones de secado se usa la cogeneración con turbina de gas (TG) como fuente de calor.

En España en los últimos años han ocurrido algunos casos de incendio en este tipo de instalaciones de cogeneración, que han supuesto pérdidas materiales muy elevadas. Por esta razón, el objetivo de este trabajo es determinar analítica y experimentalmente las condiciones operativas del secadero bajo las cuales podría comenzar un proceso de autoinflamación del alperujo y determinar el riesgo real de incendio en este tipo de instalaciones.

Para el estudio analítico, se ha planteado y validado el modelo matemático que permite calcular la temperatura y la composición de los gases de combustión a la entrada y a la salida del secadero, en función de las curvas características de la TG, de las condiciones atmosféricas, del caudal y del grado de humedad de la biomasa tratada. El modelo permite además calcular la temperatura de bulbo húmedo, que es la máxima temperatura que podría alcanzar la biomasa durante el proceso de secado y determinar la cantidad de biomasa que se puede secar completamente en función del caudal y de las condiciones de entrada de los gases de combustión.

Con estos resultados y la temperatura mínima de autoinflamación del alperujo determinada experimentalmente siguiendo la norma EN 50281-2-1:2000, se demuestra que en un proceso de secado de alperujo en condiciones normales de operación no existe riesgo de autoencendido que pueda dar origen a un incendio.

Palabras clave: alperujo, secado de biomasa, autoignición de biomasa, riesgo de incendio, cogeneración con turbina de gas

1. INTRODUCTION

Alperujo is a by-product generated in the oil mills during the olive oil extraction process by centrifugation in two phases [1]. It is mainly composed of pit fragments, part of the pulp or mesocarp and peel, with large quantities of water and a reduced portion of residual oil. Alperujo has a huge amount of water (between 60% and 75% m/m w.b.), acidic pH (5.4) and a large proportion of organic material (91%) [1]. Alperujo generates serious environmental problems due to its composition and its high production volumes. Therefore, the valorization of this residue has a vital importance. One of the most important options is the extraction treatment of the oil fraction which is still in the alperujo, called pomace oil

or “orujo”, and the used of the pomace, called “orujillo”, as a boiler and burner fuel [2]ⁱⁱ. In all valorization process it is necessary carry out a drying processⁱⁱⁱ until the maximum moisture content is 10% m/m w.b. [3].

The direct drying process^{iv} by evaporation^v is the most widely utilized with biomass using air or hot gases. During this process, wet biomass is subjected to mechanical agitation in order to facilitate heat and mass transfer, while vaporized water is dragged by the gas flow [4]. Hot gas is traditionally obtained by combustion in a conventional burner but currently, thanks to CHP development, exhaust streams from ovens, reciprocating internal combustion engines and especially from Gas Turbines (GT) are been used. Thus, drying by CHP increases energy efficiency while reduce emissions released into the atmosphere, primary energy consumption and operational cost are reduced allowing a profitability increase [5].

With regard to the drying process study, Castaño et al. (2009) presented a methodology for modelling co-current rotary dryers by differential equations with the purpose of optimizing and making more precise control of the solids drying process [6]. Golato et al. (2005) show a methodology to determine the overall heat transfer coefficient of rotary dryers applied to lemon rinds. This coefficient is one of the most important design parameters in a dryer plant [7]. Furthermore, Montero (2005) presented a mathematical model of biomass residues dryer process using a solar hybrid dryer [2].

Specifically, the alperujo drying process was experimentally studied by Arjona et al. (1999), in which the drying technical characteristics were determined in laboratory, volatile emissions, auto-ignition temperature and degradation at high temperature under different operating conditions [8]. Afterwards, this study was used by the same author as a base for developing an automatic control system of a conventional alperujo dryer feeding directly by burner gases [9]. More recently, Gómez de la Cruz et al. (2015) presented a finite element method in order to optimize alperujo conventional drying process [10].

There have been recently in Spain some fires in this kind of GT-CHP facilities, which have caused hugh material losses. Due to the fact that one of the most common breakdowns in a CHP facility is fire in the turbine air intake filters [11], in one of those disasters a hypothesis explaining that the fire could be generated by incandescent alperujo out of the drying system chimney was proposed. It could be dragged by the wind and impact with the turbine air intake filters, causing fire in them and spreading it into the system. For this reason, the aim of this study is to analytically and experimentally determine under which operational conditions could occur self-ignition of alperujo in the drying process and, as a result, it could be determined the actual fire hazard in this type of facilities.

In this analytical study, it has been proposed and validated a mathematical model which allows calculating combustion gases temperature and composition into and out of the dryer depending on the technical characteristics of the GT, atmospheric conditions, the mass flow and the moisture content of the treated biomass. The model also calculates the wet bulb temperature, which sets the maximum temperature reached by the biomass during the drying process and it determines the amount of biomass that could be completely dried depending on the flow and the inlet combustion gas conditions. Additionally it has been experimentally determined the Layer Ignition Temperature (LIT) and Powder Ignition Temperature (PIT) of the alperujo under normalized procedures [12], according to EN 50281-2-1:2000 [13]. With these results, is has been determined the operational conditions of the alperujo drying process that could generate fire risk. These results could be used to the optimization, automatic regulation and security control of the drying systems.

2. METHODOLOGY

2.1. DESCRIPTION OF THE FACILITIES

CHP Gas Turbine facilities for alperujo drying process normally count with:

- Alperujo storage ponds. These ponds are used for collecting alperujo from the oil mills with a moisture content over 70% m/m w.b. It allows alperujo to lose humidity by natural evaporation.
- Power generator. In this kind of CHP facilities, where the thermal energy production is the main aim, GT are normally used because the ratio between electrical energy and thermal energy produced is lower than 0.5. For this study case, a

15 MW “Solar Turbines” model Titan GT, working in critical summer conditions has been considered. In Fig.1 it is shown technical characteristics of the turbine considered in the study and features under ISO conditions.

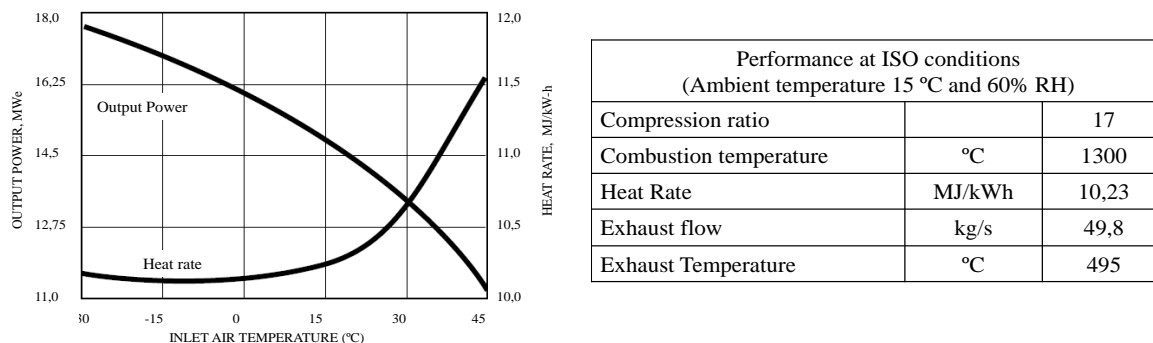


Fig. 1. Characteristic curves of the Solar Turbines Titan 130 model GT.

• The alperujo drying facility studied includes two co-current rotary dryers^{vi}, called trommel [10], in which the product and the gases are inserted at the front part and consequently, the gas with highest temperature is in contact with the product which has highest moisture content. (Fig. 2A). Alperujo from the storage ponds, with >65% m/m w.b of humidity, is mixed with semi-dry alperujo (20% m/m w.b) before it enters in the first drying line in order to reduce its moisture content until 50% m/m w.b and thus the process is optimized. Semi-dry alperujo is sent to the second drying line, where the drying process ends and the range of moisture sets from 8 to 10% m/m w.b. [9].

At the end of each trommel, combustion gases are sent to a chimney by an induced draft fan, after passing through a cyclonic filters system. Cyclones take the gas from the top of the end area of each trommel and they prevent from releasing alperujo powder into the atmosphere. Due to its small particle size, alperujo powder remains in suspension and it is dragged by the gas flow when it goes through the dryer (Fig. 2B).

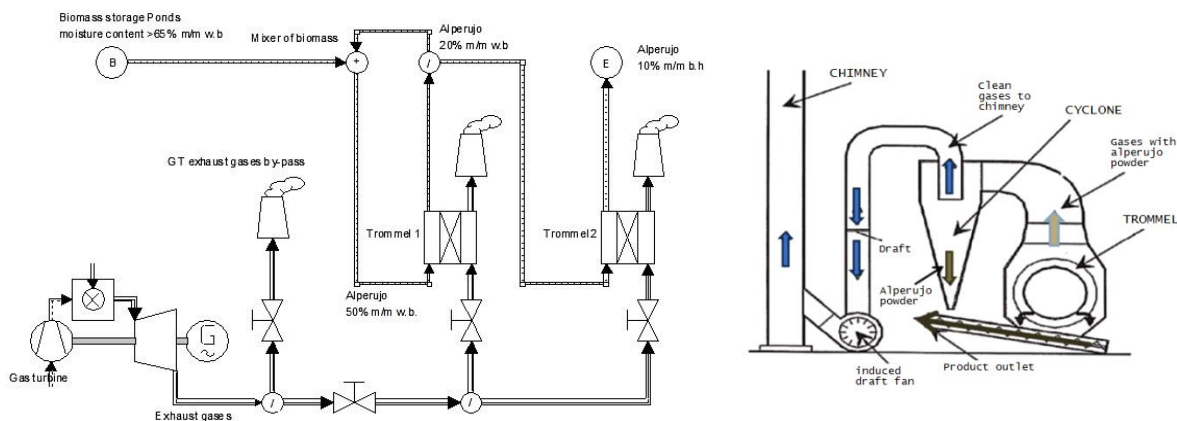


Fig. 2. A) Flowchart of Alperujo dryer system and B) Gas extraction system.

2.2. DRYING PROCESS DESCRIPTION

Alperujo has a fraction of humidity in liquid form surrounding solid particles creating a “soup” with fluid appearance, whereas, the rest of humidity is absorbed into the particles, which are porous and have an equivalent diameter under 3 mm. For this reason, drying process involves free water vaporization as well as extraction of the inner water vaporization. This process begins when the superficial free water vaporizes transferring vapour into the gas flow and generating a mass transfer mechanism inside the particles that makes inner moisture moves progressively to the surface and it keeps the drying process. As the vaporization process continues to develop, water vapour content in gases is increasing.

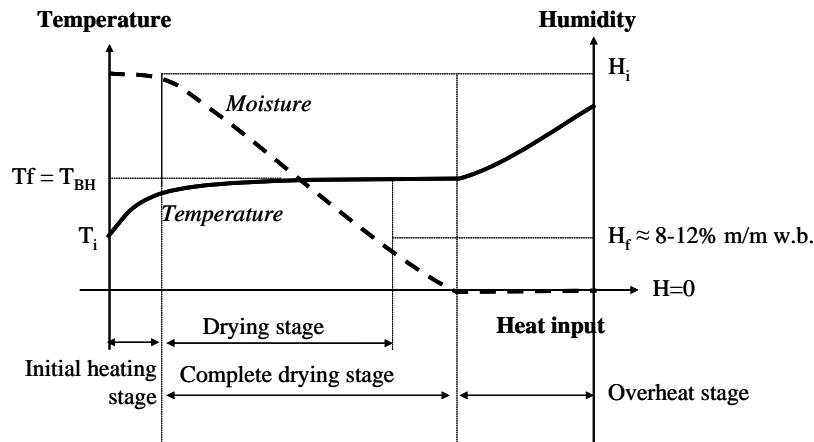


Fig. 3. Biomass drying process. Evolution of temperature and humidity of biomass.

When wet biomass enters in the dryer and it contacts with hot gases, increases its temperature and it starts to vaporize water. This evaporation causes saturation^{vii} in the atmosphere which is in contact with the biomass, noticing in these points a temperature reduction until wet bulb temperature. Therefore, under maximum heat transfer conditions, the highest temperature reached by the biomass during the drying process is the wet bulb temperature of the gases. This temperature remains practically constant until the biomass loses moisture. However, if the biomass keeps in contact with hot gases after the drying, overheating will start causing a temperature increase until thermal equilibrium with the heat source is reached or until auto-ignition temperature is exceeded and, as a consequence, combustion process begins. In a simplified mode, in Fig.3 it is observe the evolution of the biomass temperature during the development of the drying process. Gómez de la Cruz et al. (2015), [10] display the curves of alperujo temperature and humidity evolution throughout the tommel, the kinetic process of the drying and the study of the different applicable models.

2.3. EXPERIMENTAL TESTS

To determine risk fire of a given biomass it is necessary to know the minimum temperature at which ignition process could begin. This process could occur when biomass is deposited creating a layer or when biomass is dispersed in a cloud, therefore, this study determines the Minimum Ignition Temperature in Layer (MITL)^{viii} and the Minimum Ignition Temperature in Cloud (MITC)^{ix} [14 y 15] according to EN 50281-2-1:2000 [13]. Samples used in these tests were taken at a real alperujo drying facility in the south of Spain and the experiments were carried out in Laboratorio Oficial Madariaga.

Two alperujo samples were tested: one was dry alperujo and the other one was powder of alperujo retained in the cyclones (Fig.2). In Fig.4 it is shown the appearance of the two tested alperujo samples.



Fig. 4: Photographs of Alperujo. Left: dry Alperujo and right: dry powder of Alperujo.

Dry alperujo sample was taken at the end of the second drying line (Fig.2A) with 8% of moisture content, dark brown and black colored, dirty appearance and variable particle size. It was prepared drying it during 72 hours in a muffle at 70 °C (final moisture content of 1.5%). It was tested only for the MITL because the particle size was excessive to carry out the MITC test.

Alperujo powder sample, which has 7.9 % moisture content and a particle average size of 665.4 μm, was taken from the worm screw which removes the material retained in the cyclones located at the dryer gas outlet (Fig. 2B) and it is the alperujo fraction with less particle size. This sample was subjected to tests in order to determine MITL and MITC.

2.4. THERMODYNAMIC ANALYSIS

For the analytical study of the drying process, the actual temperature of the combustion gases out of the GT is determined firstly, which depends on atmospheric conditions, technical characteristics of the turbine (Fig.1) and exhaust gases composition. It can be calculated knowing the natural gas composition and the air-fuel ratio (A/F) calculated considering that this ratio is the same as the GT has when it is working under normalised ISO conditions. Exhaust gases composition is calculated using the following generalized expression of combustion with air excess.

$$C_a H_b N_c + \lambda \left(a + \frac{b}{4} \right) (O_2 + 3,76 N_2 + n_{amb} \cdot H_2O) \rightarrow a CO_2 + \left(\frac{b}{2} + \lambda \cdot n_{amb} \cdot \left(a + \frac{b}{4} \right) \right) H_2O + 3,76 \cdot \lambda \left(a + \frac{b}{4} + \frac{c}{2} \right) N_2 + (\lambda - 1) \left(a + \frac{b}{4} \right) O_2 \quad (1)$$

Thus, doing an energy balance in the GT, the enthalpy increase of the gases out of the GT is determined, as it is shown in the following equations:

Effective engine performance
$$\eta_e = \frac{3600 [s/h]}{HR [kJ/kW \cdot h]} \quad (2)$$

Fuel consumption
$$\dot{m}_f = \frac{P_e [kW] \cdot HR [kJ/kW \cdot h] \cdot \rho [kg/Nm^3]}{LHV_{GN} [MJ/Nm^3]} \quad (3)$$

Exhaust gases mass flow
$$\dot{m}_{gh-i} = \dot{m}_f [kg/s] \cdot (A/F + 1) \quad (4)$$

Heat of the exhaust gases
$$Q_g = (1 - \eta_e - p_{TG}) \frac{\dot{m}_f [kg/s] \cdot LHV_{GN} [kJ/Nm^3]}{\rho_{GN} [kg/Nm^3]} \quad (5)$$

Gas enthalpy increase
$$\Delta h_{gh} = \frac{Q_g [kW]}{\dot{m}_{gh-i} [kg/s]} = h_{g_outlet_GT_bh} - h_{g_ambient_temperature_bh} \quad (6)$$

Where P_e is the actual engine power, ρ is the natural gas density, LHV_{GN} is the natural gas heating value, m_f is the instantaneous fuel consumption, A/F is the air-fuel ratio of the combustion and p_{TG} is the percentage of losses from the envelope of the GT.

To determine the combustion gases enthalpy, the enthalpy values of the chemical substances obtained by the Coolpack® program at atmospheric pressure (0.96 bar) has been used, whose regression functions, which depend on the temperature at degrees Celsius (°C) for a temperature range between 0 °C and 700 °C, are shown in the following equations:

$$N_2 \text{ Enthalpy in kJ/kg} \quad h_{N_2}|_T = 0,00010 \cdot T^2 + 1,01384 \cdot T + 488,60773 \quad R^2 = 1,0000 \quad (7)$$

$$O_2 \text{ Enthalpy in kJ/kg} \quad h_{O_2}|_T = 0,00013 \cdot T^2 + 0,91252 \cdot T + 521,38699 \quad R^2 = 1,0000 \quad (8)$$

$$CO_2 \text{ Enthalpy in kJ/kg} \quad h_{CO_2}|_T = 0,00026 \cdot T^2 + 0,90190 \cdot T + 476,12724 \quad R^2 = 0,9999 \quad (9)$$

$$H_2O_{\text{vapor}} \text{ Enthalpy in kJ/kg} \quad h_{H_2O}|_T = -0,00009 \cdot T^2 + 2,03858 \cdot T + 2471,12047 \quad R^2 = 0,9999 \quad (10)$$

Thus, the enthalpy of wet gases blend at T(°C) temperature, in wet basis and dry basis, is calculated as the following equations show:

$$\text{Wet gases enthalpy (wet basis)} \quad h_{gh_bh} \left(\frac{kJ}{kg_h} \right) \Big|_T = \frac{\sum_i m_i \cdot h_i|_T}{\sum_i m_i} \quad (11)$$

$$h_{gh_bh} \left(\frac{kJ}{kg_h} \right) \Big|_T = \frac{m_{N_2} \cdot h_{N_2}|_T + m_{O_2} \cdot h_{O_2}|_T + m_{CO_2} \cdot h_{CO_2}|_T + m_{H_2O} \cdot h_{H_2O}|_T}{m_{N_2} + m_{O_2} + m_{CO_2} + m_{H_2O}} \quad (12)$$

$$\text{Wet gases enthalpy (dry basis)} \quad h_{gh_bs} \left(\frac{kJ}{kg_h} \right) \Big|_T = \frac{m_{N_2} \cdot h_{N_2}|_T + m_{O_2} \cdot h_{O_2}|_T + m_{CO_2} \cdot h_{CO_2}|_T + m_{H_2O} \cdot h_{H_2O}|_T}{m_{N_2} + m_{O_2} + m_{CO_2}} \quad (13)$$

Where the fuel mass per mole (C_aH_b), of the i component it is calculate depending on the number of moles of the component i in the eq.1 and its molar mass, as it is shown in eq. 14.

$$m_i \left(\frac{kg_i}{mol_{C_aH_b}} \right) = \frac{n_i \cdot PM_i}{n_{C_aH_b}} \quad (14)$$

The second step of the analytical calculation is to determine the wet bulb temperature, which sets the maximum temperature reached by the biomass during this process, as it was explained previously. Determining it depends on the thermodynamic conditions of the dryer inlet gases and the heat losses are disregarded. In this analysis, the heat exchanger length and the heat transfer coefficient are not taken into consideration because the aim of this study is to determine the maximum temperature that could reach the biomass in contact with the combustion gases. This occurs when a heat exchanger of infinite length is considered, in which the thermal equilibrium is reached with a temperature differential of zero between the biomass and the gases ("pinch point") at the end of the process. Therefore, the formulas used to determine the wet bulb temperature are:

$$\text{Relative humidity (=100\% fully saturated)} \quad \varphi = \frac{P_v}{P_{SAT_H_2O}|_T} \quad (15)$$

Water saturation pressure (in bar) at temperature T (°C)

$$p_{SAT_H_2O}|_T = e^{12,1929 - \left(\frac{4109,1}{T(^{\circ}C) + 237,65} \right)} \quad \text{for } T < 373,85^{\circ}C = T_{\text{critical_H}_2O} \quad (16)$$

Molar fraction χ of water vapour in the combustion gases at atmospheric pressure, corresponding to the vapour pressure p_v (bar):

$$\chi_{H_2O} = \frac{p_v}{P_{atm}} = \frac{n_{H_2O}}{n_{N_2} + n_{O_2} + n_{CO_2} + n_{H_2O}} \quad (17)$$

Thus, under saturation conditions, the maximum number of water moles (n_{H_2O}) at temperature T in °C

$$n_{H_2O_máx}|_T = \frac{\chi_{H_2O_máx}|_T}{1 - \chi_{H_2O_máx}|_T} \cdot (n_{N_2} + n_{O_2} + n_{CO_2}) \quad (18)$$

Therefore, wet bulb temperature T_{BH} is determined (using eq. 13) taking into account that the enthalpy of the GT outlet gases in dry basis (T_{g_i}) is the same as the enthalpy of the humidity saturated gases at T_{BH} , as it is shown in the following equality:

$$h_{gh_i_bs} \left(\frac{kJ}{kg_h} \right) \Big|_{T_{g_i}} = h_{gh_sat_bs} \left(\frac{kJ}{kg_h} \right) \Big|_{T_{BH}} \quad (19)$$

Where:

$$h_{gh_i_bs} \left(\frac{kJ}{kg_h} \right) \Big|_{T_{g_i}} = \frac{m_{N_2} \cdot h_{N_2}|_{T_{g_i}} + m_{O_2} \cdot h_{O_2}|_{T_{g_i}} + m_{CO_2} \cdot h_{CO_2}|_{T_{g_i}} + m_{H_2O} \cdot h_{H_2O}|_{T_{g_i}}}{m_{N_2} + m_{O_2} + m_{CO_2}} \quad (20)$$

$$h_{gh_sat_bs} \left(\frac{kJ}{kg_h} \right) \Big|_{T_{BH}} = \frac{m_{N_2} \cdot h_{N_2}|_{T_{BH}} + m_{O_2} \cdot h_{O_2}|_{T_{BH}} + m_{CO_2} \cdot h_{CO_2}|_{T_{BH}} + n_{H_2O_máx}|_{T_{BH}} \cdot PM_{H_2O} \cdot h_{H_2O}|_{T_{BH}}}{m_{N_2} + m_{O_2} + m_{CO_2}} \quad (21)$$

The third step in the analytical calculation is the mass balance on the drying process, using the following equations:

Biomass specific humidity in dry basis
$$H_{bs} = \frac{m_{H_2O} [kg_{H_2O}]}{m_{bs} [kg_s]} \quad (22)$$

Biomass specific humidity in wet basis
$$H_{bh} = \frac{m_{H_2O} [kg_{H_2O}]}{m_{bh} [kg_h]} = \frac{m_{H_2O} [kg_{H_2O}]}{m_{bs} [kg_s] + m_{H_2O} [kg_{H_2O}]} \quad (23)$$

Humidity rate removed in the drying process, where the initial moisture content in wet basis is H_{i_BH} , and the final moisture content in wet basis is H_{f_BH} :

$$\dot{m}_{H_2O_evap} = \dot{m}_{i_bh} \left[H_{i_bh} - \left(\frac{H_{f_bh}}{1 - H_{f_bh}} \right) (1 - H_{i_bh}) \right] \quad (24)$$

This moisture moves to the combustion gases, therefore, the additional moisture content provided per exhaust gases mass is:

$$\frac{\dot{m}_{H_2O_evap}}{\dot{m}_{gh_i}} = \frac{\dot{m}_{H_2O_evap}}{\dot{m}_{i_bh}} \cdot \frac{\dot{m}_{i_bh}}{\dot{m}_{gh_i}} = \left[H_{i_bh} - \left(\frac{H_{f_bh}}{1 - H_{f_bh}} \right) (1 - H_{i_bh}) \right] \cdot \frac{\dot{m}_{i_Bbh}}{\dot{m}_{gh_i}} \quad (25)$$

The additional moisture mass supplied to the combustion gas per fuel mole (according to eq.1), is calculated as it is shown in eq.26 and the total water mass contained in the combustion gases out of the drying process can be calculated by eq. 27

$$\frac{\dot{m}_{H_2O_evap}}{n_f} = \frac{\dot{m}_{H_2O_evap}}{\dot{m}_{gh_i}} \left(1 + \frac{A}{F} \right) \cdot PM_f \quad (26)$$

$$\frac{\dot{m}_{H_2O_total}}{n_f} = \frac{\dot{m}_{H_2O_evap} + \left(\frac{b}{2} + \lambda \cdot n_{amb} \cdot \left(a + \frac{b}{4} \right) \right) \cdot PM_{H_2O}}{n_f} \quad (27)$$

The fourth step is the energy balance on the drying process, in which the dryer efficiency is defined as the ratio between the heat used in the drying process ($\dot{Q}_{\text{sec_bms}}$) and the thermal energy variation of the combustion gases through the dryer, as it is shown in eq. 28

$$\eta_{\text{secadero}} = \frac{\dot{Q}_{\text{sec_bms}}}{\dot{m}_{gh_i} \cdot (h_{gh_i} - h_{gh_f})} \quad (28)$$

Where the heat used in the drying process per mass unit of incoming biomass (in w.b) is:

$$\frac{\dot{Q}_{\text{sec_bms}}}{\dot{m}_{i_bh}} = \frac{\dot{Q}_{\text{cal_bms_sec_}T_{bms_i}-T_{\text{evap}}} + \dot{Q}_{\text{cal_}H_2O_total_}T_{bms_i}-T_{\text{evap}}} + \dot{Q}_{\text{evap_}H_2O} + \dot{Q}_{\text{cal_}H_2O_{\text{evap_}T_{\text{evap}}-T_{gh_f}}} + \dot{Q}_{\text{cal_bms_sec_}T_{\text{evap}}-T_{gh_f}}}{\dot{m}_{i_bh}} \quad (29)$$

And where $\dot{Q}_{\text{cal_bms_sec_}T_{bms_i}-T_{\text{evap}}}$ is the heat supplied to the biomass dry fraction which enters the process from the inlet temperature to the evaporation temperature, and it is calculated based on the dry biomass specific heat (0.848 kJ/kg °C), as it is shown in eq. 30

$$\frac{\dot{Q}_{\text{cal_bms_sec_}T_{bms_i}-T_{\text{evap}}}}{\dot{m}_{i_bh}} = (1 - H_{i_bh}) c_{p_bms_sec} \cdot (T_{\text{evap}} - T_{bms_i}) \quad (30)$$

Considering that the maximum biomass temperature at the entrance of the dryer is the same as the wet bulb temperature corresponding to the atmospheric conditions, it could be calculated in the same way that evaporation temperature was calculated using the equations eq. 15 to eq. 22.

The heating heat of the liquid water contained in the biomass which enters the process ($\dot{Q}_{\text{cal_}H_2O_total_}T_{bms_i}-T_{\text{evap}}$) from the inlet temperature to the evaporation temperature, depends on the specific heat of liquid water (4.1868 kJ/kg°C) and it is calculated as it is shown in eq. 31

$$\frac{\dot{Q}_{\text{cal_}H_2O_total_}T_{bms_i}-T_{\text{evap}}}}{\dot{m}_{i_bh}} = H_{i_bh} \cdot c_{p_H_2O_liq} \cdot (T_{\text{evap}} - T_{bms_i}) \quad (31)$$

The heat supplied to evaporate the water ($\dot{Q}_{\text{evap_}H_2O}$) is calculated depending on the latent heat of vaporization λ at temperature T in °C and the initial and final moisture content of the biomass, as it is shown in eq.31.

$$\frac{\dot{Q}_{\text{evap_}H_2O}}{\dot{m}_{i_bh}} = \frac{\dot{m}_{H_2O_evap} \cdot \lambda|_{T_{\text{evap}}}}{\dot{m}_{i_bh}} = \left[H_{i_bh} - \left(\frac{H_{f_bh}}{1 - H_{f_bh}} \right) (1 - H_{i_bh}) \right] \cdot \lambda|_{T_{\text{evap}}} \quad (32)$$

Where the latent heat of vaporization λ at temperature T in °C could be calculated using a polynomial regression of the values obtained by the program Coolpack®, it is shown in eq.33

$$\lambda_{H_2O}|_T = -0,00006 \cdot T^3 + 0,01984 \cdot T^2 - 4,52713 \cdot T + 2.550,84395 \quad R^2 = 0,99547 \quad (33)$$

Additionally, $\dot{Q}_{cal_H_2O_T_{evap}-T_{gh_f}}$ is the heating heat that has to be supplied to the evaporated water from the evaporation temperature to the combustion gases outlet temperature, it is calculated from the specific heat of vapour (1.86 kJ/kg°C), as it is shown in eq. 34 and eq.35.

$$\dot{Q}_{cal_H_2O_T_{evap}-T_{gh_f}} = \dot{m}_{H_2O_evap} \cdot c_{p_H_2O_vap} (T_{gh_f} - T_{evap}) \quad (34)$$

$$\frac{\dot{Q}_{cal_H_2O_T_{evap}-T_{gh_f}}}{\dot{m}_{i_bh}} = \left[H_{i_bh} - \left(\frac{H_{f_bh}}{1 - H_{f_bh}} \right) (1 - H_{i_bh}) \right] c_{p_H_2O_vap} (T_{gh_f} - T_{evap}) \quad (35)$$

And the heat for overheating biomass ($\dot{Q}_{cal_bms_sec_T_{evap}-T_{gh_f}}$), which is transferred only if the biomass is completely dried and the process has enough time to reach an equilibrium of temperature with the exhaust gas, it is calculated as it is shown in eq.36.

$$\frac{\dot{Q}_{cal_bms_sec_T_{evap}-T_{gh_f}}}{\dot{m}_{i_bh}} = (1 - H_{i_bh}) c_{p_bms_sec} (T_{gh_f} - T_{evap}) \quad (36)$$

From the whole previous analysis it can be calculated the combustion gases temperature out of the dryer, knowing the incoming biomass flow, its initial and final moisture content, the combustion gases flow and its initial temperature, solving the following equation:

$$h_{gh_f} = h_{gh_i} - \frac{\dot{Q}_{sec_bms}}{\eta_{secadero} \cdot \dot{m}_{gh_i}} \quad (37)$$

Additionally, it can be calculated the biomass flow which can be dried per unit of mass flow of exhaust gases, knowing the initial and final moisture content of the biomass and the combustion gases temperature at the entrance of the dryer, solving the equation for different output combustion gases temperatures at the dryer:

$$\frac{\dot{m}_{i_bh}}{\dot{m}_{gh_i}} = \frac{\eta_{secadero} (h_{gh_i} - h_{gh_f})}{\frac{\dot{Q}_{cal_bms_sec_T_{bms_i}-T_{evap}} + \dot{Q}_{cal_H_2O_total_T_{bms_i}-T_{evap}} + \dot{Q}_{evap_H_2O} + \dot{Q}_{cal_H_2O_evap_T_{evap}-T_{gh_f}} + \dot{Q}_{cal_bms_sec_T_{evap}-T_{gh_f}}}{\dot{m}_{i_bh}}} \quad (38)$$

3. RESULTS

3.1. EXPERIMENTAL TESTS

The results of the MITL test, according to EN 50281-2-1:2000 [13], with the dry alperujo sample, demonstrate that a minimum temperature of 330 °C has to be reached in order to begin the combustion of the alperujo with normal particle size. This result is slightly more reduced than the result presented by Arjona et al. [8]

The test results using the alperujo sample obtained at the cyclones demonstrate that in order to begin the combustion of the alperujo powder, it has to be reached a minimum temperature of 640 °C for ignition in cloud and higher than 400 °C for ignition in layer.

3.2. THERMODYNAMIC ANALYSIS

Actual temperature of the combustion gases out of the GT:

- Natural Gas used: 94,1 % of CH_4 , 5 % C_2H_6 , 0,2% C_3H_8 and 0,5 % N_2 , molar mass 16.76 g/mole, density 0.78 kg/Nm^3 , lower heating value (LHV) 35 MJ/Nm^3 y elemental composition: $\text{C}_{1,055} \text{H}_{4,1} \text{N}_{0,010}$.
- Under ISO conditions (Ambient temperature 15 °C and 60 % RH) (see section 2.1) using equations from eq. 1 to eq. 18, the heat loss from the envelop of the GT is 5.6 % and the air-fuel ratio used at full load is 56.3 ($\lambda=3.28$).
- Under the critical ambient conditions of the study, which correspond to a hot day in summer with temperature of 37 °C, relative humidity 13% and barometric pressure 0.9757 bar:
 - Air composition (eq. 1), using eq. 15 to eq. 18, is $\text{O}_2 + 3.76\text{N}_2 + 0.04 \text{H}_2\text{O}$.
 - The GT produce 12.45 MWe at full load and the heat rate (HR) is 11.1 MJ/kWh (Fig.1). Under these operational conditions, the air-fuel ratio and the turbine heat losses are considered equal to those determined for the ISO conditions.
 - The combustion gases composition at the outlet of the turbine is (v/v): 76,0 % N_2 ; 3, 1% CO_2 ; 14,0 % O_2 and 6,9 % de H_2O , calculated using eq. 1. Molar mass 28.37 g/mole.
 - Using eq. 2 to eq. 6, the GT operational parameters are: effective engine performance: 32.4 %; Fuel consumption: 0.78 kg/s; Exhaust gases flow: 0.78 kg/s; Exhaust gases heat: 25.9 MW; Gases enthalpy increase: 578.4 kJ/kg.
 - The gas temperature at the dryer gas inlet (it is the same as the GT outlet temperature, disregarding the heat losses) is 534.9°C (808 K and $h_{\text{gh}_i\text{bh}} = 1164.3 \text{ kJ/kg}$) using eq. 7 to eq. 14

Wet bulb temperature (evaporation temperature):

- Wet bulb temperature is 67.7 °C, it corresponds to the gases enthalpy in dry basis at the dryer inlet (534.9 °C $h_{\text{gh}_i\text{bs}} = 1217.6 \text{ kJ/kg}$) using eq. 15 to eq. 21. This temperature is the maximum reached by the biomass during the drying process. In general terms, combustion gases temperature and wet bulb temperature are shown in Fig. 5 for each enthalpy value in dry basis. Particularly, the current case is shown. Considering the experimental data, combustion gases temperature at the dryer inlet of 430 °C, the biomass outlet temperature sets between 40 and 50 °C, this confirms the results showed in Fig. 5, in which the heat losses are not considered.

Mass and energy balance in the drying process:

- As it was explained previously, the alperujo temperature at the drying process inlet reaches its maximum in the wet bulb temperature under the atmospheric conditions considered (ambient temperature 37 °C and 13 % RH). Using eq. 13 to eq. 19, this temperature is 17.5 °C.

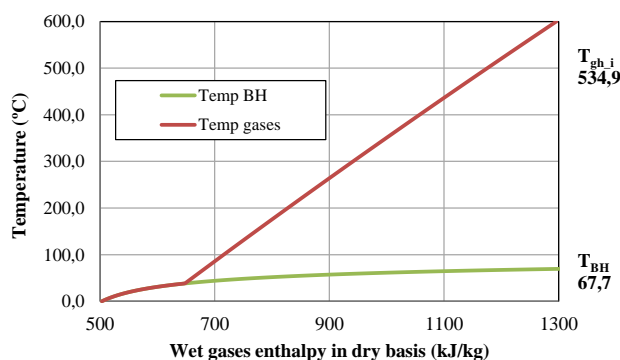


Fig. 5: Temperatura de gases a la salida de la TG y temperatura de bulbo húmedo.

- The dryer actual efficiency (eq. 28) is 95 %, calculated using actual data from the production of the drying facility: daily flow of treated biomass in w.b: 710275 kg/day with an initial moisture of 76.5 % m/m w.b and a final moisture of 8,34 % m/m w.b, the actual gases temperature at the dryer inlet is 431 °C and the gases temperature out of the dryer is 88.7 °C.
- The maximum amount of alperujo (considering different initial moisture contents) which could be completely dried and reach the overheating (Fig. 3), relative to the mass flow of the combustion gases under the critical operating condition considered, is shown in Fig. 6. In this figure it is shown the fire hazard zone, which, according to the experimental results, occurs when the solid biomass reaches a 330 °C.

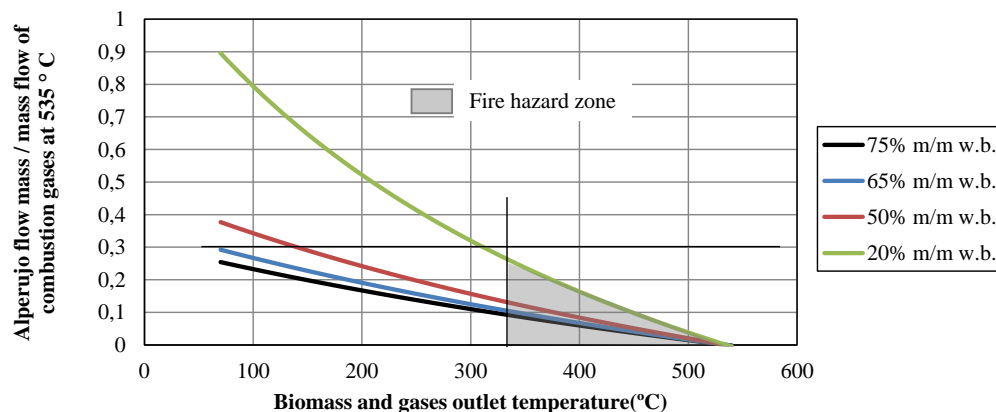


Fig. 6: Maximum mass flow of Alperujo (kg / s) that may lead to overheating per unit mass flow of GT combustion gases at 535 °C.

3.3. RESULTS ANALYSIS

According to the experimental results, the critical condition of the alperujo ignition in a co-current dryer occurs when the biomass reaches 330 °C, situation that might occur under the operational conditions showed in Fig. 6, in which, the combustion gases temperature out of the dryer exceed this temperature. However, as it was explained previously, while the biomass is wet, the maximum temperature reached will be the wet bulb temperature, which is 68 °C in the most unfavourable case.

For the drying system showed in Fig. 2 and under the critical conditions of the study, as it is seen in Fig. 6, the fire risk in the secondary drying trommel occurs when the alperujo mass flow (20 % moisture content in w.b) is under 0.27 kg/s per kg/s of combustion gases and in the primary drying trommel when the alperujo mass flow (65 % moisture content in w.b) is under 0.11 kg/s per kg/s of combustion gases. These situations could occur if the trommel inlet is partially or completely clogged and the combustion gases inlet remains constant. Under these conditions, it would be detected a gradual increase of the exhaust gases temperature at the dryer outlet (which is less than 90 °C under normal operating conditions) until it exceeds 330 °C.

It is essential to take into consideration that, under normal operating conditions, the protection systems of the dryers raise the alarm when the combustion gases temperature at the dryer outlet exceeds 90 °C and the fire extinguishing system of the facility is activated when this temperature exceeds 125 °C. Thus, under normal operating conditions, if neither the audible alarms nor the extinguishing system are activated, it could be ensured that the alperujo has not reached auto ignition conditions (330 °C) and therefore, under normal operating conditions, there is not fire risk of biomass within the trommel.

According to these experimental results, the alperujo powder cloud could not reach ignition conditions in an alperujo drying system because it would be necessary that the flying particles were in contact with hot air or a hot surface with a temperature over 640 °C, circumstance highly unthinkable because the maximum temperature of the GT gases inside

the dryer is 535 °C. However, if this alperujo powder is spread in layer, it could produce ignition if the hot gases arrive at the chimneys at 400 °C, condition which is never reached under normal operating conditions, as it was explain previously.

4. CONCLUSIONS

The minimum temperature required for alperujo combustion is 330 °C. According to the thermodynamic analysis, this temperature is not reached during the drying process fed by gases from a GT under normal operating conditions. Nevertheless, there is fire risk if the supply to any of the trommels stops completely or partially and the supply of the turbine gases remains constant, consequently, the combustion gases temperature out of the drying process would increase, and the minimum ignition temperature could be reached.

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ⁱ The alperujo organic matter is mainly composed of lignin (35%), hemicellulose and cellulose. Furthermore, alperujo has a high fat content (between 10% and 12%) and it also has water-soluble polyphenols (0.9%), fractions which provide alperujo phytotoxic properties.

ⁱⁱ “Orujillo”, due to its composition, has high energy content with a low heating value of about 20 MJ/kg, in dry basis [3]

ⁱⁱⁱ The drying process of materials with high water content, such as biomass or ceramic materials could be performance by mechanical, physical-chemical systems or by evaporation. These drying systems are classified according to the heat propagation, operating pressure, drying agent, current layout, residence time, etc.

^{iv} According to the method used to supply heat to the drying process, this could be classified into direct or indirect drying process. In direct drying, the material receives heat by direct contact with the heat transfer fluid (air, hot gases or vapour at high temperature), while in indirect drying, the material is separated from the heat transfer fluid through a heat exchanger.

^v Drying by evaporation consist in supplying the thermal energy corresponding to the water latent heat of vaporization to cause its evaporation at atmospheric pressure.

^{vi} Commonly used dryers belong to the rotary type and they can work in co-current or counter-current. In co-current systems, the biomass and the hot gases flow in the same direction, hot gases at higher temperature come into contact with wettest products, reducing volatile losses and the fire risk. Counter-current system has the advantage of achieving higher moisture reductions in the product, because driest solids come into contact with hottest gases, they have the disadvantage of increasing fire risk [4].

^{vii} When air or gas mixture is saturated to water vapour, vapour partial pressure is the same as the water saturation pressure, which depends on temperature.

^{viii} The Minimum Ignition Temperature in layer (MITL) test is made according to EN 50281-2-1:2000 [13]. It is used a sample with the matter in a thin layer of about 5 mm on a plate which is heated at an initial temperature of 400 °C using an electrical resistance. If combustion is no detected at this temperature, even after several tests, the test ends and the fact is recorded, because 400 °C is the maximum temperature considered in this tests. On the contrary, if combustion is detected at 400 °C, a new test is started, with new material, reducing 10 K the temperature each time until a temperature at which auto-ignition in the sample is not detected after 30 minutes. It is considered ignition if there is incandescence or a flame in the material, or if the temperature measured in the test is over the temperature of the hot surface defined, which implies the existence of exothermic reactions.

^{ix} The Minimum Ignition Temperature in cloud is made according EN 50281-2-1:2000 [13]. This test is performed by dispersing a powder sample in a furnace initially at 500 °C; if ignition is not detected, the test has to be repeated with a new powder sample increasing the temperature 50 K each time until lower auto-ignition temperature is found. If the sample undergoes auto-ignition at 500 °C, the test is repeated reducing the temperature at intervals of 20 K, until the lower auto-ignition temperature is found. It is considered ignition when a flash is seen at the lowest end of the furnace tube. Time delay is acceptable in ignition, but sparks without flame do not constituted ignition. This experiment is tested at a maximum temperature of 1000 °C and if the sample does not experience combustion even at this temperature, this fact is recorded.